

MULTI-OBJECTIVE MODEL FOR TIME-COST TRADE-OFF IN REPETITIVE CONSTRUCTION PROJECTS

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ABSTRACT

Repetitive construction projects are very common in construction industry. In such projects, a number of tasks are repeated in a specific sequence over a number of similar units or sections, by a set of dedicated resources. Overall performance of repetitive construction projects can be attributed to the efficient use of these dedicated resource crews for early completion of the project with minimum total project cost. Existing methodologies optimize the schedule with respect to a single objective, to minimize project duration or maximize resource work continuity or minimize project costs. However, scheduling decisions for repetitive construction projects are multi-objective and hence a balance between resource work continuity, project duration and project total cost must be established.

In this paper, a genetic algorithm based multi-objective optimization model for scheduling repetitive construction projects is presented. The model comprises three modules: a resource-driven scheduling module; a cost module; and a multi-objective optimization module. The scheduling module ensures minimum project duration and maximum crew work continuity for a set of resource crew formations. The cost module computes project total costs. The optimization module generates several trade-off solutions between project duration and project total cost. Construction project planners can use this trade-off information to select resource crew formations for each task and the corresponding project schedule. A numerical example from the literature is analysed to illustrate the use and capabilities of the model.

KEYWORDS: Repetitive Construction Projects, Optimal Scheduling, Crew Work Continuity, Genetic Algorithms, Linear Schedule, Multi-Objective Optimization, Time-Cost Trade-Off

INTRODUCTION

A repetitive project comprises of a number of similar units, where a number of tasks are performed in a specific sequence. Examples of such projects include mass housing projects, high-rise building constructions, highways, railway lines, airport runways, oil and gas pipelines, water and sewer lines, multi-span bridges, tunnels, etc. In such projects, a set of resources (i.e. a crew) repeat the same task in various units of the project, moving from one unit to another. As each dedicated resource crew move from one unit to another performing a specific task, a crew is required to wait if the crew of the preceding task has not finished its work in the particular unit (Yang and Ioannou 2001). For effective resource management, such unforced idleness must be avoided to provide continuity of work for each resource crew.

As widely reported in literature, network scheduling methods, such as critical path method (CPM), have major drawbacks while scheduling repetitive construction projects (Reda 1990; Suhail and Neale 1994; Harris and Ioannou 1998; Hegazy and Wassef 2001). The main shortcoming of CPM in repetitive project scheduling is its inability to ensure crew

work continuity. To overcome the drawbacks of network techniques for scheduling repetitive construction projects, many other approaches have been developed. These include ‘Line of balance (LOB)’ method, ‘Vertical production method (VPM)’, ‘Linear scheduling method (LSM)’ and Repetitive scheduling model (RSM)’. These scheduling methods for repetitive construction projects focus on maximizing crew work continuity by enabling each crew to finish work in one location of the project and move promptly to the next without work breaks. These methods aim to finish the project at the earliest for a set of crew formations, but do not consider alternative resource crew formations.

Different resource crew formations may be considered for performing tasks in a repetitive construction project. Task durations and hence project duration varies with different crew formations. Several methods have been developed for determining the crew formations that minimize the project duration or cost. Selinger (1980) proposed a dynamic programming model that considers crew formations as decision variables to minimize the project duration, but ignores work interruptions or costs in decision making. Russel and Caselton (1988) developed a two-state variable, N-stage dynamic model that considers a set of possible durations (for different available crew formations) and a set of interruption durations as decision variables in order to minimize the project duration. El-Rayes and Moselhi (2001) presented a model based on dynamic programming formulation, designed to identify an optimum crew formation and interruption option for each activity in the project that leads to minimum project duration. Reda developed a linear programming based direct cost optimization model which assumes constant production rate for each activity and provides complete work continuity. Senouci and Eldin (1996) presented a dynamic programming formulation for scheduling of non-serial activities to determine the project time-cost trade-off, which determines possible project durations and their minimum project total costs. Ipsilantis (2007) introduced a multi-objective linear programming model for scheduling linear repetitive projects, which takes into consideration cost elements regarding the project’s duration, the idle time of resources, and the delivery time of the project’s units. Long and Ohsato (2009) presented a method of optimal scheduling for repetitive construction projects with several objectives as project duration, project cost, or both of them. The model combines project duration and project cost into a single objective. There is a pressing need for models that can help project planners in generating and evaluating feasible trade-offs between project duration and project cost in order to choose the most suitable schedule.

In this paper, a multi-objective optimization model is presented for selection of optimal resource crew formations while scheduling repetitive construction projects. This genetic algorithm (GA) based multi-objective optimization approach generates a trade-off between project duration and project total costs for different crew formations.

PROPOSED MODEL

The proposed model has three main modules which guide the optimal scheduling for repetitive construction projects. (1) The scheduling module that establishes, for a particular crew combination, the start and finish times for each task in each unit, so that the project can be completed in the shortest possible time and the resource crews remain idle for minimum possible time. (2) The cost module that calculates project costs for the crew formations under consideration, crew idle time, scheduled project duration and scheduled unit completion times. (3) The optimization module that facilitates to search different feasible combinations from the available crews for each task and generate a trade-off between project duration and project total cost.

Model Formulation

Objectives

The proposed model has two main objectives: 1) to minimize project duration, and 2) to minimize project total cost. These objectives form the fitness function of the optimization algorithm while selecting the optimal resource crew combinations for each task. The secondary objective of maximizing crew work continuity is accomplished through the scheduling module.

Constraints

Technologically driven precedence relationships between successive tasks and availability of resource crew for performing a particular task at a unit are the two primary constraints in scheduling RCPs. These are incorporated in forward as well as backward pass of the scheduling module. The third requirement in scheduling RCPs, i.e. crew work continuity, is not treated as mandatory, and hence set as an objective in the backward pass of the scheduling module.

Decision Variables

The resource crew formations for each task are the major decision variables that are selected through the optimization module. The scheduled start and finish times for each activity are determined through scheduling algorithm. The resultant project duration, unit completion times and crew work-breaks are obtained through the scheduling algorithm.

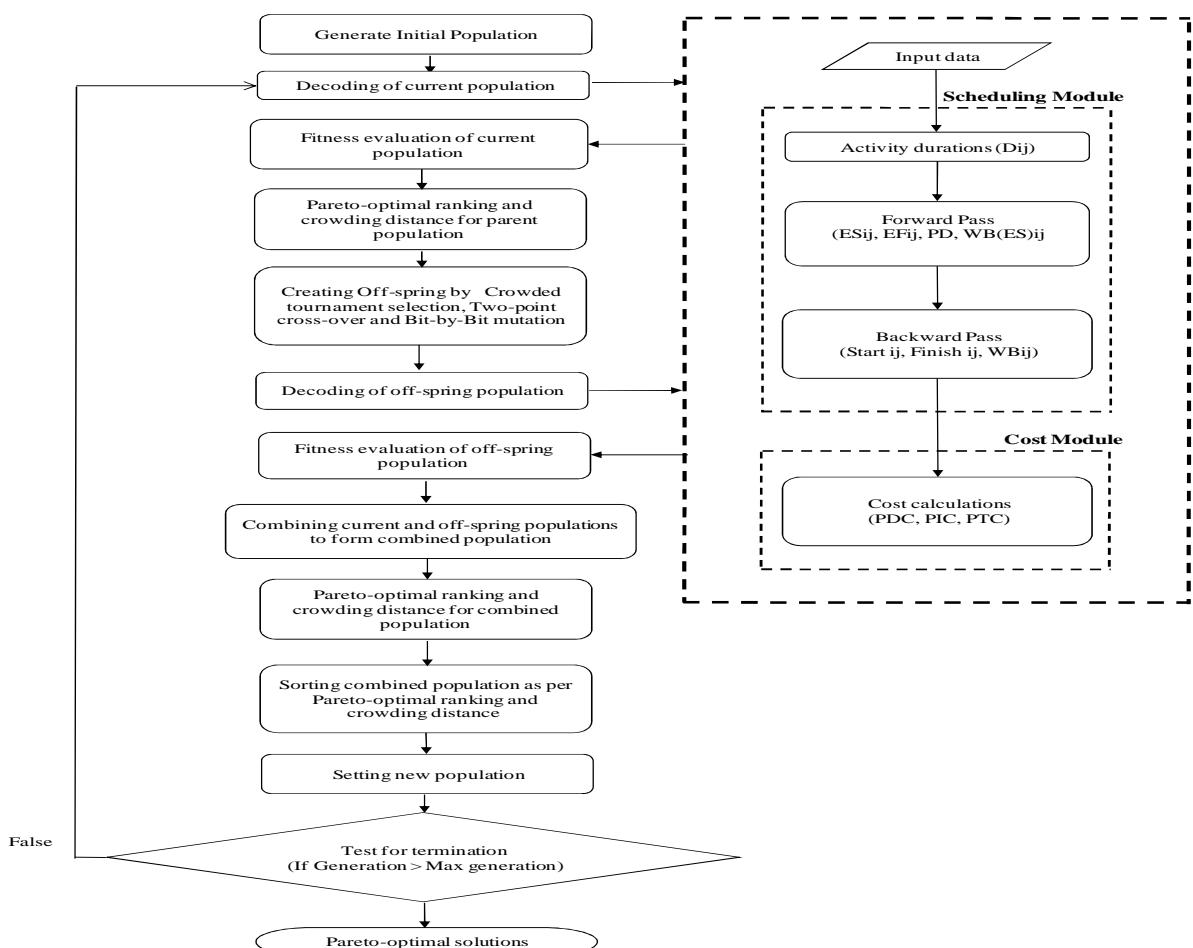


Figure 1: Flowchart for Schedule Optimization to Minimize Project Duration and Project Costs

SCHEDULING MODULE

The scheduling module is formulated to determine, for a particular set of resource crew formations, the start and finish times for each task in each unit, overall project duration and the crew work-breaks. Initially the forward pass of this module schedules all activities as early as possible and determines the earliest possible project duration. It also calculates work-breaks for resource crews of each task, as they move from one unit to another. In the backward pass these crew work-breaks are minimized by pulling activities ahead in time, without extending the project duration.

Forward Pass

In repetitive construction projects, as resource crew of a particular task finishes its work at a unit and moves to the next unit, it can start work only if the crew of the preceding task has finished its work in that unit. Thus the earliest start of an activity is governed by precedence logic and crew availability constraints. To start a task (i) at any unit (j), the preceding task ($P_{(ik)}$) must be finished at unit (j) and the crew of task (i) must have finished work in previous unit ($j-1$).

Beginning with task(s) without any predecessor in the first unit and proceeding through successive units ($j=1$ to J), possible start times complying with precedence logic and crew availability are first determined.

Possible start time according to precedence logic,

$$SPL_{ij} = [EF_{(P_{(ik)})j} + Lag_{(P_{(ik)})i}]_{max} \quad (1)$$

Possible start time according to crew availability,

$$SCA_{ij} = EF_{i(j-1)} + Int_{ij} \quad (2)$$

Earliest start time complying with both, precedence logic and crew availability, is now calculated.

$$ES_{ij} = max[SPL_{ij}, SCA_{ij}] \quad (3)$$

Thus, earliest finish time,

$$EF_{ij} = ES_{ij} + D_{ij} \quad (4)$$

This step computes the earliest possible start and finish for each task at each location; and hence the earliest time to complete the project with particular resource crews.

If a task has higher production rate than its preceding task, the resource crew is required to wait until the preceding task is not finished at that unit. As the crew work continuity is not targeted at this stage, the resulting schedule contains the work-breaks for crews of certain tasks at some units after completing the same task at the previous unit. Crew work-breaks for individual activities as per early start schedule,

$$WB(ES)_{ij} = ES_{ij} - EF_{i(j-1)} - Int_{ij} \quad (5)$$

The earliest possible project completion time can be computed as,

$$PD = max[EF_{ij}] \quad (6)$$

Backward Pass

Once earliest time to complete the project is established by forward pass calculations, starting with the last task, the activities are shifted from their earliest times to reduce the crew work-breaks, to the extent possible without affecting the earliest project duration.

The scheduled start time and the finish time for minimum work-breaks are determined in this stage.

The shift time to pull activities forward to reduce work-breaks is given by,

$$\text{Shift}_{ij} = \min \left[\begin{array}{l} S_{i(j+1)} - EF_{ij} - Int_{i(j+1)} \\ S_{(s_{(jk)})j} - EF_{ij} - Lag_{i(s_{(jk)})} \end{array} \right] \quad (7)$$

Start time for minimum work-breaks,

$$S_{ij} = ES_{ij} + Shift_{ij} \quad (8)$$

Corresponding finish time,

$$F_{ij} = S_{ij} + D_{ij} \quad (9)$$

Once the start and finish time for minimum work-breaks, under duration constraint, for a task are established, the preceding task is scheduled for the minimum work-breaks. The computational procedure is continued till the first task is scheduled for minimum work breaks. Minimum crew work-breaks can now be determined.

Work-breaks for activity (ij)

$$WB_{ij} = S_{ij} - F_{i(j-1)} - Int_{ij} \quad (10)$$

Work-breaks for crew of task (i)

$$WB_i = \sum_{j=1}^J WB_{ij} \quad (11)$$

COST MODULE

Costs associated with a project can be related to the various attributes of the project schedule. Total project cost comprises of: (1) the direct cost, (2) the indirect cost, (3) crew idle time cost, (4) project delay penalty (or project early completion bonus), and (5) unit completion delay penalty (or unit early completion bonus).

Project Direct Cost

The direct cost includes costs of various resources required to perform and complete all tasks of the project. The method of execution and the selected resource crew formation determine the durations for a task in respective units and hence the direct cost of the task.

$$PDC = \sum_{i=1}^I \sum_{j=1}^J [(Q_{ij} * MCR_i) + (D_{ij} * LCR_i) + (D_{ij} * ECR_i)] \quad (12)$$

Where,

MCR_i = material cost rate per unit quantity of task ' i '

LCR_i = labour cost rate per day for task ' i '

ECR_i = equipment costs rate per day for task ' i '

Project Indirect Cost

Indirect costs include all such expenses which cannot be attributed to a specific task, but are essentially required

to be spent during the execution of the project. Some of these expenses are required for initial mobilization of plants and machineries, necessary permissions for execution, project site establishment, etc are independent of the project schedule. These are fixed indirect costs. Cost of common equipment and plants, cost of utilities, project execution overheads like site office expenses, cost of supervision, etc are required to be spent throughout the project execution. These are the variable indirect costs that depend on project duration.

$$PIC = FIC + PD * RIC \quad (13)$$

Where,

FIC = fixed indirect cost

RIC = rate of indirect cost

Crew Idle Time Cost

Typically in a RCP, if work continuity is not accomplished for crew of each task, the resource crew remains idle for the period of work-breaks. Such idle resources, when not performing work, will cost. This crew idle time cost is given by,

$$CITC = \sum_{i=1}^I \sum_{j=1}^J (WB_{ij} * RCIT_i) \quad (14)$$

$RCIT$ = crew idle time cost per day

Project Delay Penalty and Early Completion Bonus

Every project contract specifies the time limit to complete it. If the scheduled project completion time is beyond the stipulated time limit, there is a scheduled delay in project completion. Such delay may invite penalty for delayed project completion.

$$PDP = (PD - SPD) * LD \quad (15)$$

Where,

SPD = stipulated project duration

LD = liquidated damages per day

If the project is scheduled to be completed earlier than stipulated project completion time limit, it will fetch bonus for early completion.

$$PECB = (SPD - FD) * RECB \quad (16)$$

Where,

$PECB$ = project early completion bonus

$RECB$ = project early completion bonus per day

Unit Completion Delay Penalty and Unit Early Completion Bonus

Sometimes the project is delivered unit-wise upon the completion of individual units. Project contract stipulates the time-frame for delivery of each unit as well as the applicable penalties for delayed completion of each unit. If a unit is

scheduled to be completed beyond the stipulated time limit, it will invite the delay penalty.

$$UCDP = \sum_{j=1}^J [(UCT_j - SUCT_j) * RUCDP_j] \quad (17)$$

If any unit is scheduled to be completed and delivered earlier than the stipulated time limit, it will attract the incentives for early completion.

$$UECB = \sum_{j=1}^J [(SUCT_j - UCT_j) * RUECB_j] \quad (18)$$

Where,

UCT_j = scheduled completion time of unit ' j '

$SUCT_j$ = stipulated completion time of unit ' j '

$UCDP$ = unit delayed completion penalty for the project

$RUCDP_j$ = per day delayed completion penalty for unit ' j '

$UECB$ = unit early completion bonus for the project

$RUECB_j$ = per day early completion bonus for unit ' j '

Project Total Cost

Total project cost is the sum of direct cost, indirect cost, crew idle time cost, project delay penalty and unit completion delay penalty.

$$PTC = PDC + PIC + CITC + PDP + UCDP \quad (19)$$

Modified project total cost can be obtained by considering the applicable incentives.

$$PTC = PDC + PIC + CITC + PDP + UCDP - PEBC - UECB \quad (19a)$$

OPTIMIZATION MODULE

The present model uses genetic algorithm (GA) to search various possible resource crew combinations and obtain a set of optimal crew combinations that simultaneously minimize project duration and project total costs. GA works on the principle of natural selection, by creating an environment where large number of possible solutions to a problem can compete with one another, and only the 'fittest' survive. A population of solutions evolve better solutions in successive generations leading towards near optimal ones. Genetic algorithms are considered to be one of the most effective techniques for determining optimal solutions when the solution space is fairly large and complex (Goldberg, 1989; Deb, 2010). GA primarily involves three operators, viz, reproduction, crossover and mutation. These operators apply on a population of chromosomes. Each chromosome represents all the decision variables of a feasible solution. Initial population is randomly generated. Consecutive generations evolve by applying the operators of reproduction, crossover and mutation.

The proposed model uses elitist non-dominated sorting genetic algorithm (NSGA-II) to search various possible resource crew combinations. This multi-objective genetic algorithm evaluates each solution of the population from two fitness values, the project duration and the project total costs. Figure 1 depicts the search procedure of this GA-based

optimization module and its integration with the proposed scheduling module and cost module. The optimal resource crew combination for each task is selected by using higher level information for the solutions on Pareto-optimal front obtained from the last generation.

ILLUSTRATIVE EXAMPLE

To validate the proposed model, a concrete bridge example used by Moselhi and El-Rayes (1993) is analysed. The example was originally presented by Selinger (1980), and later analysed by Russell and Caselton (1988) and others. The project consists of four similar units, each involve five repetitive tasks in sequence: excavation, foundations, columns, beams, and slabs. All the tasks follow finish to start relationship with the predecessor task with no lag time. Task quantities in each unit, available crew formations, corresponding production rates and costs of the tasks at each unit are given in Table 1. The trade-off crew combinations for minimum project duration and minimum project cost are obtained by using the proposed model.

Table 1: Details of Quantities, Crew Formations, Productivity Rates and Costs

Task	Quantity (M^3) in Each Unit				Crew Formation (R)	Production Rate (M^3/Day)	Material Cost (\$/ M^3)	Labor Cost (\$/ M^3)	Equipment Cost (\$/ M^3)
	1	2	3	4					
Excavation	1147	1434	994	1529	1	91.75	0	340	566
Foundation	1032	1077	943	898	1	89.77	92	3804	874
					2	71.81	92	2853	655
					3	53.86	92	1902	436
					1	5.73	479	1875	285
Columns	104	86	129	100	2	6.88	479	2438	371
					3	8.03	479	3000	456
					1	9.90	195	3931	315
Beams	85	92	101	80	2	8.49	195	3238	259
					3	7.07	195	2544	204
					4	5.66	195	1850	148
					1	8.73	186	2230	177
Slabs	0	138	114	145	2	7.76	186	1878	149

The problem was analysed by the proposed model with the following GA parameters. 1) Chromosome: binary strings; 2) Length of each string = 8 bits; 3) Population size = 50; 4) Maximum generations = 500; 5) Crossover rate = 1.0; 6) Probability of mutation = 0.05. After running the elitist non-dominated sorting genetic algorithm for 500 generations, the trade-off solutions of the Pareto-optimal front are obtained. Figure 2 shows these trade-off solutions forming the Pareto-optimal front.

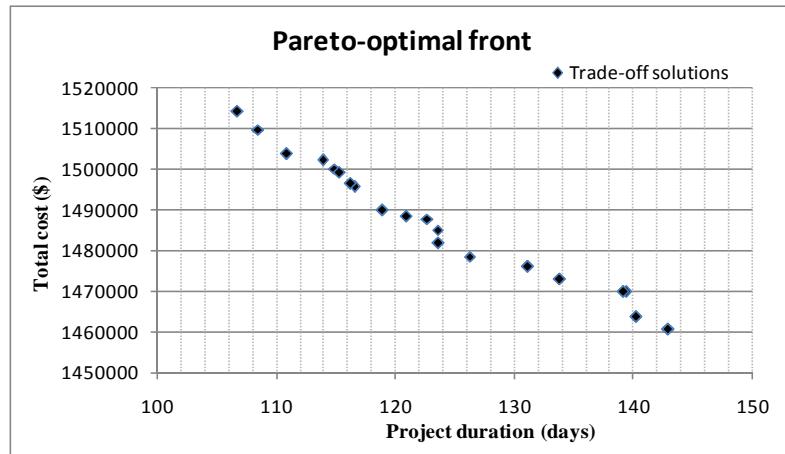


Figure 2: Trade-Off Solutions between Project Duration and Project Total Cost

Trade-off solutions on Pareto-optimal front are listed in table 2. There exists no feasible solution which is better than any one of this Pareto-optimal set in terms of both objectives. At least one solution of this Pareto-optimal set is better in terms of both objectives than any other feasible solution. The user can, now, consider other higher level information to choose one most suitable solution from this Pareto-optimal set.

Table 2: Pareto-Optimal Set

Solution	Project Duration (Days)	Project Cost (\$)		Solution	Project Duration(Days)	Project Cost(\$)
1	106.8	1514097		11	122.7	1487709
2	108.5	1509708		12	123.5	1485069
3	110.9	1503788		13	123.6	1481620
4	113.9	1502255		14	126.2	1478494
5	114.9	1500068		15	131.1	1476030
6	115.3	1499003		16	133.8	1472904
7	116.3	1496334		17	139.1	1469903
8	116.6	1495679		18	139.3	1469758
9	119.0	1489759		19	140.3	1463668
10	120.9	1488195		20	142.9	1460543

If trade-off solution number 3 is selected, after due considerations, the corresponding optimal crew formations are 1, 1, 3, 3 and 1 for excavation, foundations, columns, beams, and slabs, respectively. Corresponding linear schedule is shown in figure 3. Corresponding project duration is 110.9 days, total crew idle time is 7.5 days and project total cost is \$1503788.

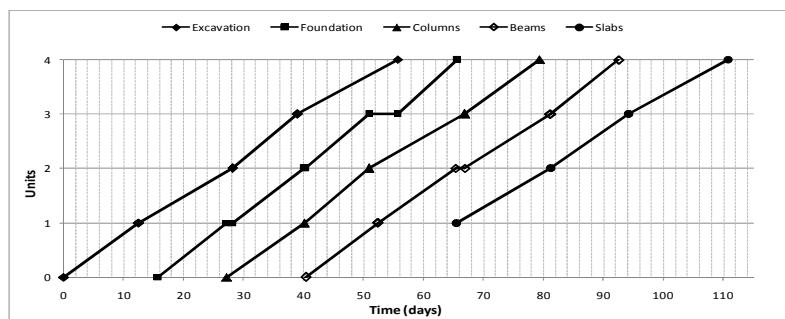


Figure 3: Linear Schedule for Project Duration of 110.9 Days

CONCLUSIONS

In this paper a model for optimal scheduling of repetitive construction projects has been described. The proposed model optimally assigns the resource crew formation to each task and schedules the activities to minimize project duration and project total cost. The model incorporates a scheduling module to determine project duration, a cost module to compute corresponding project costs and an optimization module to search for feasible crew formations for each task to find optimal trade-off solutions in order to complete the project at the earliest with minimum total cost. This model uses GA for searching the possible solutions from the complex solution space.

As GA operates with a population of solutions simultaneously, the model allows users to examine tradeoffs between the project duration and the corresponding project total cost. This model will help the planners of repetitive projects to decide the most suitable crew formations to minimize the project duration as well as project total cost. The bridge construction example from literature is analysed to validate the proposed model. It is observed that this model provides more efficient solutions for optimizing project duration and project total cost.

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